

Type I Seesaw Mechanism, Lepton Flavour Violation and Higgs Decays

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Abstract. We review and update the current phenomenological constraints on minimal type I seesaw extensions of the Standard Model in which New Physics content can be probed at the electroweak scale. In this class of models, the flavour structure of the neutrino Yukawa couplings is determined by the requirement of reproducing neutrino oscillation data. The strongest constraints on the seesaw parameter space are imposed by the very recent upper limit on $\mu \rightarrow e\gamma$ decay rate. Searches of non-standard Higgs boson decays into a light and a heavy neutrino may also provide an independent test of these seesaw scenarios.

1. Introduction

The recent discovery of the Higgs boson at the Large Hadron Collider (LHC) [1, 2] with a mass $m_h \sim 125$ GeV marks an important breakthrough in our understanding of the mechanism of electroweak (EW) symmetry breaking and is by itself an extraordinary success of the Standard Model (SM) of Elementary Particles.

On top of the discovery of the Higgs boson, there are still several open questions which the SM, in the way it is conceived now, cannot explain. In particular, New Physics must be advocated to explain the outcome of the flavour neutrino oscillation experiments, which provide compelling and indubitable evidence that at least two neutrinos have non-zero masses, several orders of magnitude smaller than the other SM charged fermions masses, and that the three neutrino flavours mix. These very small neutrino masses can be linked to a new physical scale of Nature that, in general, is not related to the EW symmetry breaking scale.

One of the most successful mechanism of neutrino mass generation is the well known type I seesaw scenario [3], in which the SM is extended with at least two heavy SM singlet fermions, $N_{1,2}$, usually dubbed right-handed neutrinos, that have Yukawa-type interactions with the SM Higgs and left-handed doublets. If further symmetries are not imposed, such neutrino Yukawa couplings explicitly break lepton number and a Majorana mass term for the SM neutrinos is generated at tree-level after the decoupling of the heavy fermions $N_{1,2}$.

In the following we consider the type I seesaw scenarios studied in [4, 5, 6, 7] in which the right-handed neutrino mass scale is set in the TeV range, that is $M_{1,2} \sim (100 - 1000)$ GeV. This class of models predicts a rich low energy and collider phenomenology and, for this reason, the full seesaw parameter space is tightly constrained by different sets of data: neutrino oscillation data, neutrinoless double beta decay, EW precision tests and charged lepton flavour violating processes and right-handed neutrino production/detection at colliders.

As discussed below, the unknown seesaw parameter space can be conveniently expressed in terms of the size of the neutrino Yukawa couplings (y) and the heavy Majorana neutrino masses ($M_{1,2}$). The most conservative bound on a combination of these parameters is set by current experiments searching for $\mu \rightarrow e \gamma$ decay.

In the case of $M_{1,2} \lesssim m_h$ it is also possible to probe the neutrino Yukawa interactions looking for non-standard Higgs boson decays into a light and a heavy Majorana neutrino [8, 7, 9, 10, 11].

All the present limits on the seesaw parameter space are summarized in Figs 1 and 2.

2. Constraints on the seesaw parameter space

The mixing between the new singlet SM heavy Majorana fermions $N_{1,2}$ and the SM light neutrinos generate charged and neutral current interactions between $N_{1,2}$ and the SM gauge/Higgs bosons, which can in principle be tested in low energy and collider experiments for masses $M_{1,2} \sim (100 - 1000)$ GeV. The relevant parts of the interaction Lagrangian are in this case

$$\mathcal{L}_{CC}^N = -\frac{g}{2\sqrt{2}} \bar{\ell} \gamma_\alpha (RV)_{\ell k} (1 - \gamma_5) N_k W^\alpha + \text{h.c.}, \quad (1)$$

$$\mathcal{L}_{NC}^N = -\frac{g}{4c_w} \bar{\nu}_{\ell L} \gamma_\alpha (RV)_{\ell k} (1 - \gamma_5) N_k Z^\alpha + \text{h.c.}, \quad (2)$$

$$\mathcal{L}_H^N = -\frac{gM_k}{4M_W} \bar{\nu}_{\ell L} (RV)_{\ell k} (1 + \gamma_5) N_k h + \text{h.c.} \quad (3)$$

The couplings $(RV)_{\ell k}$ ($\ell = e, \mu, \tau$ and $k = 1, 2$) arise from the mixing between heavy and light Majorana neutrinos and, therefore, are suppressed by the seesaw scale. They can be conveniently parametrized as follows [5]:

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_3}{m_2 + m_3} \left| U_{\ell 3} + i\sqrt{m_2/m_3} U_{\ell 2} \right|^2, \quad \text{NH}, \quad (4)$$

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_2}{m_1 + m_2} \left| U_{\ell 2} + i\sqrt{m_1/m_2} U_{\ell 1} \right|^2 \simeq \frac{1}{4} \frac{y^2 v^2}{M_1^2} |U_{\ell 2} + iU_{\ell 1}|^2, \quad \text{IH}, \quad (5)$$

$$(RV)_{\ell 2} = \pm i (RV)_{\ell 1} \sqrt{\frac{M_1}{M_2}}, \quad \ell = e, \mu, \tau, \quad (6)$$

where U denotes the neutrino mixing matrix and $v \simeq 174$ GeV. Notice that the relative mass splitting of the two heavy Majorana neutrinos must be very small, $|M_1 - M_2|/M_1 \ll 1$, due to the current upper limit on the effective Majorana mass probed in neutrinoless double beta decay experiments [4, 5]. In this case, the flavour structure of the neutrino Yukawa couplings is fixed by the neutrino oscillation parameters [4, 5, 12] and the two heavy Majorana neutrinos form a pseudo-Dirac fermion: $N = (N_1 \pm iN_2)/\sqrt{2}$. The parameter y in the expressions above represents the largest eigenvalue of the matrix of the neutrino Yukawa couplings [5]:

$$y^2 v^2 = 2 M_1^2 \left(|(RV)_{e1}|^2 + |(RV)_{\mu 1}|^2 + |(RV)_{\tau 1}|^2 \right). \quad (7)$$

2.1. Charged lepton flavour violation: $\mu \rightarrow e \gamma$

In the case of a seesaw mass scale $M_{1,2}$ in the TeV range considered here, the most stringent constraint on the size of the neutrino Yukawa couplings is set by the very recent upper limit on $\mu^+ \rightarrow e^+ \gamma$ branching ratio reported by the MEG Collaboration [13]: $\text{BR}(\mu \rightarrow e \gamma) < 5.7 \times 10^{-13}$ at 90% confidence level. Taking the best fit values of the neutrino oscillation parameters [14], we can estimate the typical size of neutrino Yukawa couplings:

$$y \lesssim 0.026 \quad \text{for} \quad M_1 = 100 \text{ GeV}. \quad (8)$$

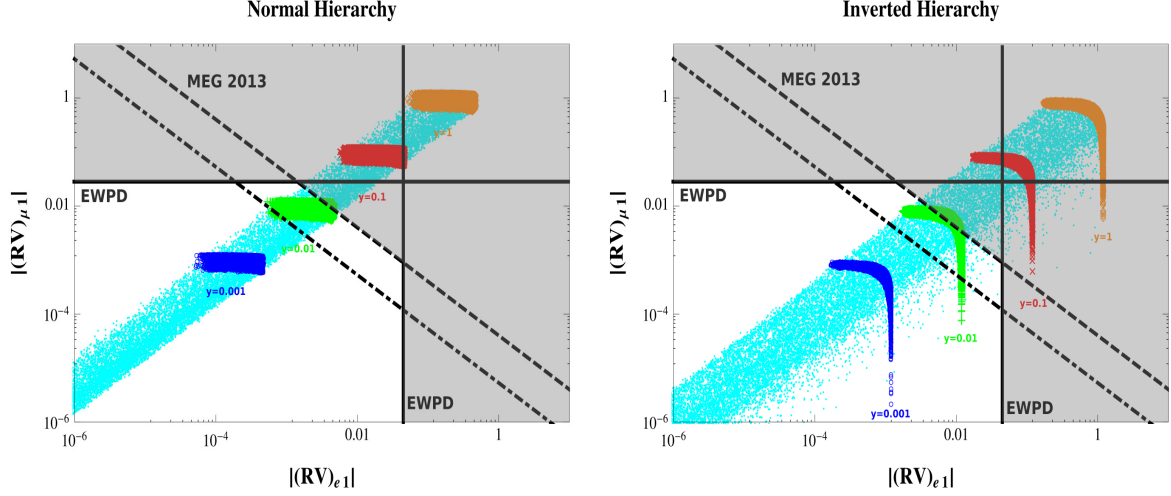


Figure 1. Correlation between $|(RV)_{e1}|$ and $|(RV)_{\mu 1}|$ for $M_1 = 100$ GeV in the case of normal (left panel) and inverted (right panel) light neutrino mass spectrum. The regions corresponding to four different values of the neutrino Yukawa eigenvalue y are highlighted. The cyan points correspond to random values of $y \leq 1$. The dashed line represents to the present MEG bound [13], $B(\mu \rightarrow e \gamma) \leq 5.7 \times 10^{-13}$. The dot-dashed line coincides with $B(\mu \rightarrow e \gamma) = 10^{-14}$.

We implement in Fig. 1 all the constraints on the effective couplings $(RV)_{\mu 1}$ and $(RV)_{e1}$ which come from the requirement of reproducing neutrino oscillation data, from EW precision data and from the current upper limit on $\mu \rightarrow e \gamma$. The seesaw mass scale is fixed at benchmark value: $M_1 = 100$ GeV. From Fig. 1, it is manifest that the allowed ranges of the right-handed neutrino couplings $|(RV)_{\mu 1}|$ and $|(RV)_{e1}|$, in the case of normal (left panel) and inverted (right panel) light neutrino mass spectrum, are confined in a small strip of the overall representative plane. This corresponds to the scatter plot of the points which are consistent with the 3σ allowed ranges of the neutrino oscillation parameters [14]. The region of the parameter space which is allowed by the EW precision data, is marked with solid lines. The region allowed by the current bound on the $\mu \rightarrow e \gamma$ decay rate is indicated with a dashed line, while the dot-dashed line shows the projected MEG sensitivity reach, *i.e.* $\text{BR}(\mu \rightarrow e \gamma) \sim 10^{-14}$. The scatter points corresponds to different values of the maximum neutrino Yukawa coupling y : $y = 0.001$ (blue \circ), *ii*) $y = 0.01$ (green $+$), *iii*) $y = 0.1$ (red \times), *iv*) $y = 1$ (orange \diamond) and *v*) an arbitrary value of the Yukawa coupling $y \leq 1$ (cyan points).

As depicted in Fig. 1, in the case of a light neutrino mass spectrum with inverted hierarchy a strong suppression of the $\mu \rightarrow e \gamma$ decay rate is possible for specific values of the measured neutrino parameters. Indeed, using the standard parametrisation of the neutrino mixing matrix U one can show that for fixed values of the mixing angles θ_{12} , θ_{23} and of the Dirac (δ) and Majorana (α_{21}) phases, $|U_{\mu 2} + iU_{\mu 1}|^2$ has a minimum for [5, 6]

$$\sin \theta_{13} = \frac{c_{23}}{s_{23}} \frac{\cos 2\theta_{12} \cos \delta \sin \frac{\alpha_{21}}{2} - \cos \frac{\alpha_{21}}{2} \sin \delta}{1 + 2c_{12} s_{12} \sin \frac{\alpha_{21}}{2}}. \quad (9)$$

At the minimum

$$\min(|U_{\mu 2} + iU_{\mu 1}|^2) = c_{23}^2 \frac{(\cos \delta \cos \frac{\alpha_{21}}{2} + \cos 2\theta_{12} \sin \delta \sin \frac{\alpha_{21}}{2})^2}{1 + 2c_{12} s_{12} \sin \frac{\alpha_{21}}{2}}. \quad (10)$$

Therefore, the $\mu \rightarrow e \gamma$ branching ratio, that is proportional to eq. (10), is highly suppressed if the Dirac and Majorana phases take CP conserving values, mainly: $\delta \simeq 0$ and $\alpha_{21} \simeq \pi$. In

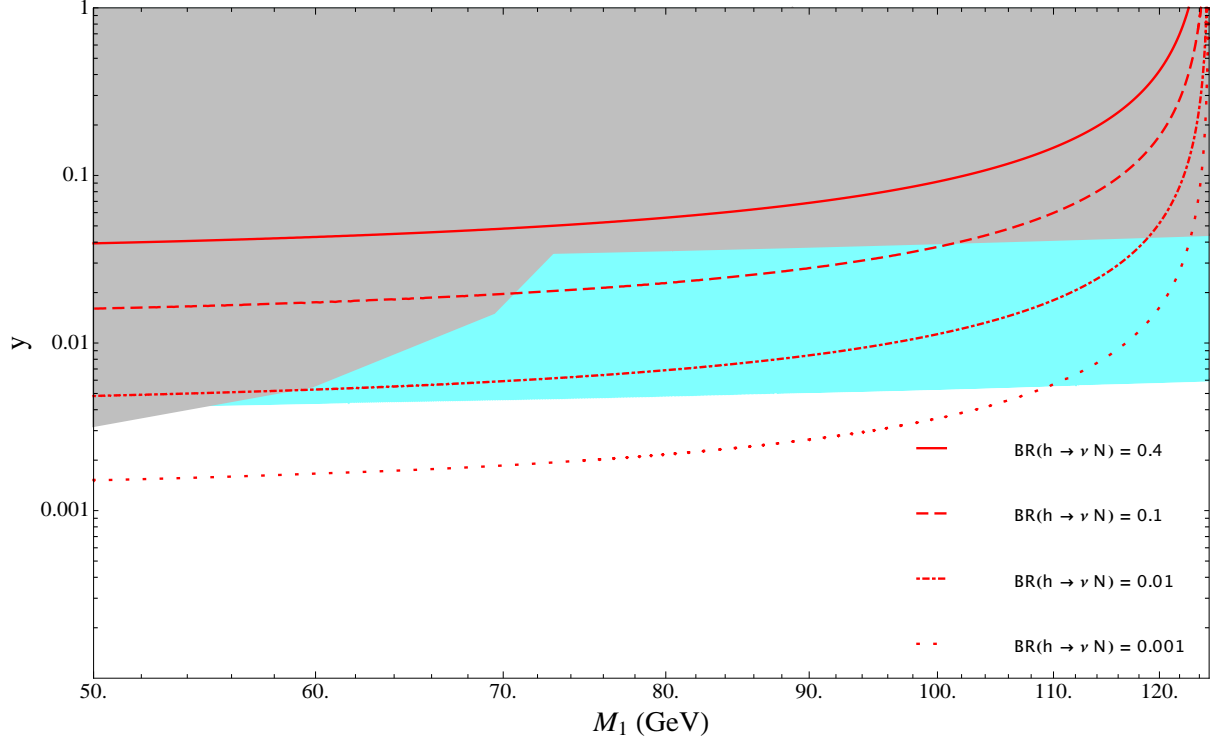


Figure 2. Values of the maximum neutrino Yukawa coupling y probed by Higgs decays into N for $m_h = 125$ GeV. The grey region is excluded by LEP2 data [15] and searches of lepton flavour violation [13]. The cyan area represents the region of the parameter space which can be probed by the MEG experiment with the projected sensitivity to $\text{BR}(\mu \rightarrow e\gamma) = 10^{-14}$.

this case, from eq. (9) we get a lower bound on the reactor angle, *i.e.* $\sin(\theta_{13}) \gtrsim 0.13$, which is in agreement with the global fit results [14]. On the other hand, assuming CP violating phases, $\min(|U_{\mu 2} + iU_{\mu 1}|^2) \approx 0$ is possible, provided θ_{12} and the Dirac and Majorana phases δ and α_{21} satisfy the following conditions: $\cos \delta \cos(\alpha_{21}/2) + \cos 2\theta_{12} \sin \delta \sin(\alpha_{21}/2) \approx 0$ and $\text{sgn}(\cos \delta \cos \frac{\alpha_{21}}{2}) = -\text{sgn}(\sin \delta \sin \frac{\alpha_{21}}{2})$.

We remark that the upper limit given in (8) is of the same order as the bottom Yukawa coupling, $y_b = m_b/v \simeq 0.024$. Therefore it is interesting to explore the possibility to produce (pseudo-Dirac) heavy neutrinos N at present and forthcoming collider facilities through non-standard Higgs boson decays, mainly $h \rightarrow \nu_{\ell L} + \bar{N}$, $\bar{\nu}_{\ell L} + N$.

2.2. New Higgs decay channel: $h \rightarrow \nu N$

In the case of $M_1 \lesssim m_h \sim 125$ GeV, it is possible to put limits on the seesaw parameter space looking for production of the right-handed neutrinos in non-standard Higgs boson decays: $h \rightarrow \nu N$ (see *e.g.* [8, 7, 9, 10, 11]). In this case, the Higgs decay rate is directly related to the neutrino Yukawa coupling y defined in eq. (7):

$$\begin{aligned} \Gamma(h \rightarrow \nu N) &\equiv \sum_{\ell=e,\mu,\tau} (\Gamma(h \rightarrow \nu_{\ell L} \bar{N}) + \Gamma(h \rightarrow \bar{\nu}_{\ell L} N)) \\ &= \frac{1}{16\pi} y^2 m_h \left(1 - \frac{M_1^2}{m_h^2}\right)^2. \end{aligned}$$

Taking as benchmark values $m_h = 125$ GeV and $M_1 = 100$ GeV, one gets $\Gamma(h \rightarrow \nu N)/\Gamma(h \rightarrow b\bar{b}) \simeq 0.19 (y/0.05)^2$, that turns out to be sizable if the upper limit on the Yukawa coupling y , obtained using the MEG upper bound (8) is saturated. Conversely, the search for the Higgs decay $h \rightarrow \nu N$ may provide limits on the parameters of the low scale seesaw scenario which are competitive to those from the searches for the $\mu \rightarrow e \gamma$ decay, when $m_h > M_1$ [7]. On the other hand, in the case $M_1 > m_h$ the exotic Higgs decay channels are, $h \rightarrow \nu N \rightarrow \nu \nu Z$, $\nu \ell W$ which have a rate suppressed by the fourth power of y as well as by the three-body decay phase space.

In Fig. 2 it is shown the correlation between y and the seesaw scale M_1 , corresponding to different values of $\text{BR}(h \rightarrow \nu N)$ and the Higgs boson mass $m_h = 125$ GeV. The region in grey is excluded by the combined data on $\mu \rightarrow e \gamma$ decay [13] and the search for heavy singlet neutrinos in Z boson decays at LEP2 [15]. It follows from the plot that the present bounds on the low scale seesaw parameter space do not preclude the possibility of a Higgs boson decaying into a heavy and a light neutrino with a branching ratio of roughly 10%. We also show in the plot as a cyan area the projected sensitivity reach of the MEG experiment searching for the $\mu \rightarrow e \gamma$ decay with a branching ratio $\text{BR}(\mu \rightarrow e \gamma) \gtrsim 10^{-14}$, which may allow to exclude $\text{BR}(h \rightarrow \nu N) \gtrsim 1\%$ for $M_1 \gtrsim 100$ GeV.

3. Conclusions

Minimal type I seesaw extensions of the Standard Model with right-handed neutrino masses at the EW scale predict by a very rich phenomenology and are tightly constrained by both low energy observables and collider searches. In the minimal scenario only two new fermion representations $N_{1,2}$ are introduced, which are Standard Model singlets and have Yukawa-type couplings to the Higgs and lepton doublets, usually referred to as neutrino Yukawa couplings. The flavour structure of such interactions is univocally fixed by the requirement of reproducing the data on the neutrino masses and mixing. The existing low energy constraints imply that the two heavy right-handed neutrinos form a pseudo-Dirac pair, $N \equiv (N_1 \pm iN_2)/\sqrt{2}$, thus preventing the possibility to observe a possible signature of lepton number violation in this class of scenarios [4, 5]. The phenomenological relevant seesaw parameter space can be conveniently expressed in term of the seesaw mass scale $M_1 \approx M_2$ and the largest neutrino Yukawa eigenvalue y .

All the constraints on y and M are reported in Figs 1 and 2. The strongest bounds are derived from the very recent upper limit on $\mu \rightarrow e \gamma$ decay rate released by the MEG experiment [13]: $\text{BR}(\mu \rightarrow e \gamma) < 5.7 \times 10^{-13}$ at 90% confidence level. If the MEG experiment eventually observes the $\mu \rightarrow e \gamma$ decay with a branching ratio $\text{BR}(\mu \rightarrow e \gamma) > 10^{-14}$, the low scale type I see-saw scenario may be directly tested at LHC through non-standard Higgs boson decays $h \rightarrow \nu N$ decays [7]. On the other hand, if no positive signal is detected in the MEG experiment, this will lead to a more stringent limit on the neutrino Yukawa coupling y that will exclude for the moment the possibility of producing and detecting the new heavy pseudo-Dirac neutrino N .

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